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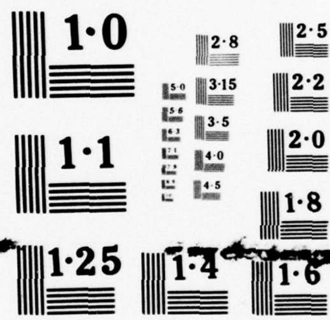
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

UPPER OCEAN THERMAL STRUCTURE FORECAST
EVALUATION OF A MODEL USING SYNOPTIC DATA

by

William Fawver Johnson

September 1977

Thesis Advisor: R. L. Elsberry

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A one-dimensional model ~~(Camp, 1976)~~ is used to simulate ocean thermal structure response to synoptic scale atmospheric forcing data at six locations, for a period of 20 days in August 1974 and 40 days from 21 November to 31 December 1974. The atmospheric forcing data (Solar Radiation, Total Heat Flux and Marine Winds) were obtained from Fleet Numerical Weather Central (FNWC) Primitive Equation and Marine Wind Models. Data used to initialize and verify the ocean thermal structure originated from bathythermograph → next page

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Upper Ocean Thermal Structure Forecast Evaluation of a Model Using Synoptic Data

by

William Fawver Johnson
Lieutenant, United States Navy
B.S., University of Washington, 1971

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

A one-dimensional model (Camp, 1976) is used to simulate ocean thermal structure response to synoptic scale atmospheric forcing data at six locations for a period of 20 days in August 1974 and 40 days from 21 November to 31 December 1974. The atmospheric forcing data (Solar Radiation, Total Heat Flux and Marine Winds) were obtained from Fleet Numerical Weather Central (FNWC) Primitive Equation and Marine Wind Models.Data used to initialize and verify the ocean thermal structure originated from bathythermograph data stored at FNWC. Length of simulation ranged from 72 hours to 36 days and was limited by the length of continuous historical data available for study. Results show the forcing functions contain sufficient resolution to define diurnal and synoptic time scale events. When the model is run using these forcing functions it produces changes in the mixed-layer depth and mixed-layer temperature on the same time scales. The magnitude of these changes ranged typically from diurnal fluctuations of 20 m/day and .3°C during summer conditions to synoptic scale deepening of 50 m and cooling by 2°C in 36 days during winter conditions. These results were verified when observations were present in this area. The capability now exists to produce real time dynamic ocean thermal profiles in areas of infrequent observations and also to forecast changes in ocean thermal structure up to 72 hours from the time of an observation.

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I. INTRODUCTION AND BACKGROUND

The ocean thermal structure affects Naval Operations particularly in the field of Antisubmarine Warfare (ASW) since acoustic sensor performance is influenced by the ocean medium. This influence leads to enhancement or degradation of acoustic sensor capabilities. Therefore to optimize mission effectiveness it is necessary to have an accurate description of the ocean medium, determine the impact of the medium on the acoustic sensor and modify tactics/operations accordingly. Fleet Numerical Weather Central (FNWC) is currently providing acoustic performance products to operational forces. These products are based on an ocean thermal structure analysis derived from Bathythermograph (Bathy) observations and ocean thermal structure history. Methods and details are found in the U. S. Naval Weather Service Numerical Environmental Products Manual (1975). The major shortcoming of this analysis is that determination of the ocean thermal structure is dependent on the frequency and density of observations. Currently about 200 Bathy observations are taken each day in the Northern Hemisphere so that a major portion of the ocean thermal structure analysis is essentially a time-averaged history. The sophistication of current and future generation acoustic performance models dictates that oceanic conditions be determined, simulated and forecast with better precision and resolution than FNWC currently provides, particularly in areas of infrequenty Bathy observations.

Numerous research models exist which have parameterized the processes that determine the ocean thermal structure. Factors such as advection,

diffusion, heat and salinity, momentum and turbulent energy transfer, and profile stability all interact to produce a dynamic ocean thermal structure. The influence of these factors depends on the time and space scales of the events/phenomena to be modeled. The one-dimensional modeling effort began with Kraus and Turner (1967) and was followed by Denman (1973), Pollard, Rhines and Thompson (1973), Elsberry, Fraim and Trapnell (1976), Kim (1976) and Camp and Elsberry (1977). Each of these groups modeled the physical processes that determine the ocean thermal structure with varying degrees of success.

Camp and Elsberry (1977) demonstrated that, given initial ocean thermal structure information and sequential weather reports at Ocean Weather Ship (OWS) locations, a one-dimensional model could simulate much of the upper ocean thermal response to atmospheric fluctuations of heat and stress. It is the purpose of this study to determine the feasibility of using this dynamic ocean model to provide ocean thermal profiles based on atmospheric forcing data derived from synoptic-scale FNWC fields. Although the model is structured so that modification can be made to tailor or tune specific processes to meet local conditions, it is not the intention of this study to tune the Camp and Elsberry model with the observed data. In view of the confidence limits of the operational data it is difficult to separate data errors from the errors attributable to parameterization of the physical processes. Neither is the purpose to demonstrate the superiority of this particular model over other available models. Another point to be emphasized is that this model is not applicable to all oceanic regimes, in particular those dominated by advective or salinity effects. Rather it is intended to

demonstrate that dynamic models can be used to produce ocean thermal profiles which respond to physical processes and are representative of real world conditions. In determining the feasibility of coupling the dynamic model with the synoptic scale atmospheric forcing fields three factors were evaluated: 1) initialization from Bathy observations provided by FNWC; 2) atmospheric forcing function resolution and variability; and 3) model results.

II. MODEL THEORY

The Camp (1976) model used in this study uses an energy balance approach to determine the ocean thermal structure response to atmospheric forcing. For modeling purposes the thermal structure of the ocean is represented to a depth of $N\Delta Z$ by N isothermal slabs of ΔZ = 2.5 m thickness. Surface heat and energy fluxes are computed and the resulting energy distributed within the water column over a time interval of Δt = 1 hr. For each time interval the model begins by determining the magnitude and direction of the heat flux at the atmosphere/ocean interface and calculating the temperature change in the water column caused by the heat flux. The resulting temperature profile is given by the following equations:

$$T_{1(t+\Delta t)} = T_{1(t)} + \frac{\Delta t}{\rho_o C_p} [-QT_{(0,t^*)} + QS_{(0,t^*)} - QS_{(\Delta Z,t^*)}]$$

$$T_{N(t+\Delta t)} = T_{N(t)} + \frac{\Delta t}{\rho_o C_p} [QS_{(-N\Delta Z,t^*)} - QS_{(-(N+1)\Delta Z,t^*)}]$$

In these equations QS represents solar radiation while QT represents the sum of latent, sensible and back radiation at the interface during the interval t* between t and $t+\Delta t$. Positive values of QS indicate flux into the ocean while positive values of QT represent heat flux into the atmosphere. Solar radiation is distributed below the surface by absorbing 50% in the first meter and absorbing the remainder as $EXP(-\gamma Z)$. The extinction coefficient, γ, remained constant at .002 cm^{-1} for this study after Camp (1976).

The resulting temperature is tested for positive gradients. This test for convective instability is valid if: a) advection processes are negligible in comparison to the processes which distribute heat vertically from the air/ocean interface; b) density changes due to salinity variations are negligible within the well-mixed layer of the water column; and c) density changes due to compressibility are negligible within the well-mixed layer. If instability is found, the water column is mixed until the temperature profile becomes stable. Mixing results in an isothermal layer from the surface to the depth of free convection. The change in potential energy caused by free convection (ΔPE_c) is calculated by:

$$\Delta PE_c = \int_D^o \delta TZdz \approx \sum_{N=1}^{NN-1} \Delta PE_c(N) = \frac{1}{2}\rho_o g\alpha(\Delta Z)^2 \sum_{N=1}^{NN-1} N(T_N - T_{N+1}) \quad (1)$$

in which δT = change in temperature resulting from free convection, D = depth of free convection and $NN = \frac{D}{\Delta Z}$. For free convection, $\Delta PE_c < 0$.

Mixing of stable profiles requires an expenditure of energy. Assuming a steady state for the turbulent energy so there is no storages. The quantity of energy available for turbulent mixing at the N+1 level is governed by the following equation:

$$E_T = E_n + E_c - E_p$$

In this equation E_T = turbulent kinetic energy available for mixing for N levels, E_n = mechanically generated turbulent kinetic energy for N levels, E_c = turbulent kinetic energy generated by free convection for N levels, and E_p = quantity of turbulent kinetic energy previously

expended to mix the layer to depth N. These quantities are defined by:

$$E_m = [\rho_o W^3 \, EXP(-N\Delta Z/H]\Delta t \qquad (2)$$

$$E_c = -R \sum_{N=1}^{NN-1} \Delta PE_c(N) \qquad (3)$$

$$E_p = \sum_{i=k}^{N-1} \Delta PE_n(i) = \sum_{i=i}^{N-1} \rho_o g\alpha N(\Delta Z)^2 (T_N - T_{N+1}) \qquad (4)$$

Parameters used in equations (2)-(4) are defined as follows: W = average wind over the time interval, H = scale depth of 50 meters used by Camp (1977) and R = .15 after Gill and Turner (1976). R represents the fraction of turbulent kinetic energy generated by free convection that is not dissipated and thus is available for entrainment processes. Therefore, whenever $E_T > \Delta PE_m$ for N levels there is energy available for turbulent mixing to the N+1 level. In cases where there is insufficient energy to mix a full layer ($E_T < \Delta PE_m$) then a partial mix is applied by the method established by Thompson (1976).

Diffusion below the well-mixed layer depth is accounted for by $\frac{\partial T}{\partial t} = Av \frac{\partial^2 T}{\partial z^2}$, where Av = .5 $cm^2 sec^{-1}$ after Haney and Davis (1976). For each time interval diffusion is calculated before mixing and applied to the temperature profile after mixing.

The heat content of the model temperature profile is determined at each time step by $\sum_{N=1}^{NMAX} \rho_o C_p (T_N - T_{NMAX})$ and is compared with the heat content of observations. The differences in heat content at t=0 represent the heat lost by removing positive gradients from the profile used for initialization. Further differences in heat content are indicative of advective/local processes not parameterized by the model, or of inaccurate surface heat fluxes.

III. DATA

The data for this study were extracted from the FNWC historical data files at six locations for the periods 8 August to 28 August 1974 and 21 November to 31 December 1974. The six locations listed in Table I correspond to OWS positions, and were chosen to provide temporal ocean data records at a fixed point. Two types of data were extracted; the first was the atmospheric forcing functions and the second was the Bathy observations.

The forcing functions extracted were; Solar Radiation (SOLARAD-FNWC catalog number A11), Total Heat Flux (THF-FNWC catalog number A18) and Marine Winds (VVWW-FNWC catalog number A27). The SOLARAD and THF fields were computed as part of the heating package of the FNWC Primitive Equation (PE) Model (Kaitala, 1974) while the Marine Winds were calculated by the Marine Layer Wind Model. Detailed descriptions of these models are found in the U. S. Naval Weather Service Numerical Environment Products Manual (1975).

Values of the forcing functions at the latitude and longitude of the OWS were extracted from the FNWC 63x63 grid field values by a Bessel interpolation routine that used the nearest 16 grid points. Four instantaneous values were available during each 24-h period, corresponding to synoptic times of 00, 06, 12 and 18 GMT. The 00 and 12 GMT data points are from the FNWC 00 and 12 GMT analysis while the 06 and 18 GMT data are 6-h forecasts from 00 and 12 GMT respectively.

The 6-hourly synoptic data then had to be interpolated to the 1-h time step of the model. For the Marine Winds a curve generated by a

cubic spline routine was passed through the synoptic values and intermediate hourly values were determined. This is probably realistic considering the horizontal scale of the systems represented on the 63x63 grid, which can only evolve rather slowly. However, the 6-hourly solar radiation values were inadequate to define the diurnal cycle. It was decided to define values at the hour of sunrise/sunset (SOLARAD=0) and the expected peak value before curve fitting. The maximum solar radiation was assumed to occur at local noon and was determined by applying Lamber's Law:

$$\frac{I_N}{I_H} = \frac{\sin\alpha_N}{\sin\alpha_H} \, q^{\left(\frac{1}{\sin\alpha_N} - \frac{1}{\sin\alpha_H}\right)}$$

where $\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos h$. In these equations, ϕ = latitude, δ = declination, I = intensity, h = local hour, N = noon, H = hour and q = moisture mass absorber (assumed constant at .7). The underlying assumption is that the SOLARAD value calculated in the PE model incorporated moisture and cloud cover effects and would change slowly in time. Thus the ratio should remain nearly constant. A value for local noon was set by multiplying the closest synoptic value by the ratio determined by Lambert's Law. Figure 1 compares the solar radiation values before and after this technique has been applied for OWS PAPA during December. Note that non-zero insolation values occur at only one synoptic time (00 GMT). A cubic spline curve through the data points at sunrise, the synoptic time, local noon and sunset was used to determine hourly values. A value for sensible, latent and back radiation (SLB) was calculated at the synoptic times by subtracting the unadjusted SOLARAD from the THF fields. The SLB is a sum of all heat

exchange processes other than solar radiation across the atmosphere/ocean interface. A cubic spline curve through the SLB radiation values was used to estimate hourly values. Final hourly values for total heat flux were then calculated by adding the adjusted solar radiation to SLB.

Bathy observations were obtained from the FNWC historical files. The 4D Format File consists of bathys received at FNWC by message and represents the Bathys used in their operational analysis. Bathy observations selected for study were normally required to be within a 100 NM (185 km) radius of the OWS position during the period studied. However, the radius of selection for OWS H was limited to 60 NM (111 km) due to the high spatial variability caused by its proximity to the Gulf Stream. Temperature profiles used to initialize the model were generated by linearly interpolating the observations to 2.5 m intervals and then converting to an average temperature for each 2.5 m slab. Positive temperature gradients encountered were set to isothermal for initialization purposes.

IV. DISCUSSION OF RESULTS

Before interpreting the model results it is first necessary to evaluate the Bathy data used for initialization. (See Table I for the number of Bathys available in each period.) The quality of the Bathys available for analyses/study is dependent on several factors; the probe and recording equipment accuracy; the operator's precision in reading the depth versus temperature profile and encoding it into a standard message format; the number of errors introduced in transmission circuits; and errors introduced by data processing in preparing the observations for analysis or storage for postanalysis recall. In addition to these errors it is necessary to determine the variability of the Bathy observations within the 100 nm radius of the OWS. The variability of an area is a function of the spatial homogeneity and temporal continuity of the surrounding water mass. Temporal variability above the seasonal thermocline is attributable to atmosphere/ocean interchanges of heat and momentum fluxes plus horizontal advection while below the seasonal thermocline variations are primarily due to advection processes. The variability of each area was found by overplotting all the observations occurring in the period studied. Figure 2 depicts a Bathy overplot for OWS PAPA from 21 November to 31 December 1974. In this case the temperature variance below the seasonal thermocline is the same magnitude as for the surface temperature, which suggests that significant advective affects are present below the seasonal thermocline. Also noted are several observations that contain unrealistic gradients. Spatial inhomogeneities are not significant since all observations were

within 10 nm of the OWS location cited in Table I. The variability below the thermocline decreased for the period 8 August to 28 August at OWS PAPA suggesting a decrease in advective activity. This suggests that a means of parameterizing the magnitude of advection in an area could be determined by calculating the temporal change in heat content below the seasonal thermocline. As expected the largest variability of Bathy observations occurred at OWS HOTEL, ranging from 5°C at the surface to 10°C below the seasonal thermocline. The majority of this variability arises from the spatial inhomogeneity associated with the Gulf Stream and its meandering flow. Unrepresentative profiles would be generated by the model in areas where temporal variability below the seasonal thermocline exists since the model simulates changes above the seasonal thermocline. Spatial inhomogeneities can be controlled by varying the area from which Bathys are considered for initialization and verification. Thus in ocean frontal regions such as the Gulf Stream the radius of the Bathy search should be reduced.

The model results are separated into three cases for discussion; for each of the cases one example was chosen from the six OWS locations studied. The first case has a net heating of the water column, the second shows a balance between daily solar heating and cooling by SLB radiation and the third has net cooling under winter conditions.

A. HEATING CYCLE

An example at OWS PAPA was chosen to illustrate model performance in cases with net heating, since three-hourly Bathys were available for most of the period between 03 GMT 9 August and 03 GMT 28 August 1974. Total surface heat flux for the period is shown in Figure 3. Positive

values represent heat lost by the water column. In this case daily solar radiation dominates over the SLB radiation, which remains fairly constant over the period. As a result, net heating of the well mixed layer should result. The wind stress (Figure 4) during the period was very small except for 72 hours of slightly larger values centered at day 6 and an 84-hour period centered at day 16. Note that these atmospheric forcing functions resolve and show variations at both the diurnal and synoptic time scales.

The response of the model well-mixed layer temperature (MLT) to the atmospheric forcing is depicted in Figure 5 and shows clearly diurnal fluctuations as well as a net increase in temperature over the 19 day period. Diurnal changes in the model MLT (equivalent to sea surface temperature - SST) averages about 0.5°C with a maximum of .75°C at day 9, while the observations show more erratic diurnal changes for example on day 1. The fluctuations of .5°C and .8°C at 06 GMT and 18 GMT appear to be unrealistic. One likely source of error in this data is the lack of precision in encoding the Bathy observation from the sounding trace by different observers. A further comparison can be made by looking at the FNWC SST analysis values. The FNWC SST shows less amplitude than the data or model values on a diurnal time scale. Plotted values correspond to the data as would be expected since the analysis contains these observations. However, during days 12 and 14 the FNWC SST analysis differs from the observations by more than 0.5°C. Figure 6 shows the slab depth (depth of isothermal layer to nearest 2.5 m increment), model mixedlayer depth (MLD), and observed MLD. MLD for this study was defined as the depth at which the temperature is .2°C less than the isothermal temperature. The distance between the two values is an inverse measure

of the thermal gradient below the well mixed layer. Diurnal changes in the model MLD are as great as 22 meters (day 1), while the largest MLD changes in the observations are approximately 20 meters during days 8, 15 and 17. Also noted is a high frequency data oscillation that is non periiodic and of varying amplitude throughout the 19 day period. Examples are found in day 1 and 7. Two factors contribute to the rapid fluctuations in the data MLD. Errors in reading and encoding the Bathy sounding trace are certainly reflected in this data since small errors in reading the temperature can lead to large errors in the MLD due to its definition of the depth .2°C cooler than the isothermal or sea surface temperature. A second error is a result of the FNWC 4D Format used as a source of historical data. Unfortunately, this format records depth information to only the nearest tens of feet. When the Bathy data MLD for each 24-h period are averaged the synoptic time scale trends are more readily apparent.

Between days 6 and 15 the model-predicted MLD is too shallow. It is significant that the model results show better agreement whenever the wind induced turbulence mixes to a greater depth and redistributes the heat accumulated in the upper layers. The increase in stress at day 15 provides an example of this point. This is indicative of the need for tuning the model for light wind conditions. Another important point is that the selection of the initialization profile can make substantial differences in the model performance. The model was run at OWS PAPA for 72 hours commencing at 00 GMT 15 August 1974 (corresponding to day 6 in Figure 6) and produced the slab depth and MLD shown in Figure 7. Model and data show little correlation. However, when the model is initialized three hours later at 03 GMT the correlation of the data with the model results improves as shown in Figure 8.

When the model was run at the other five OWS locations similar model results occurred, with the MLD and MLT fluctuating on a diurnal scale as well as a synoptic scale. Verification of the results proved inconclusive due to the sparcity of data.

B. DIURNAL CASE

This second case is presented to demonstrate the affects of the diurnal MLD migration when the net heat flux is nearly zero. A case at OWS INDIA for the period 08 GMT 9 August to 08 GMT 28 August 1974 was chosen. The total heat content over the period is nearly constant with the daytime solar heating being balanced by the back radiation, sensible and latent heat (Figure 9). The wind stress (Figure 10) contains repeated cycles of light stress followed by moderate stress of 48 to 72 hr duration. This period is probably associated with the passage of atmospheric storms. The amplitudes of the diurnal variations of the slab depth and MLD (Figure 11) were nearly constant during the first 4.5 days. Then the slab depth and MLD increase in response to the increase in wind stress. As the wind decreases in day 6 the slab depth again decreases. When moderate stress commences at day 9 and lasts until day 12 the slab depth and MLD are again forced deeper. With a period of weak stress from day 12 to 15 the MLD and slab depth again decrease. During the last three days an atmospheric storm is responsible for the moderate stress appearing in this period. As a result of the storm, turbulent mixing forces the MLD and slab depth deeper causing a cooling which is also shown in the profile of Figure 12.

Once again the forcing functions have shown sufficient resolution to produce diurnal and synoptic time scale events. The ability to resolve and simulate these events has a significant impact on the capability

to predict acoustic sensor performance. In a qualitative sense the "afternoon affect" has long been known to operators of acoustic sensors. The model, coupled with the atmospheric forcing functions, has demonstrated the ability to simulate fluctuations on a diurnal time scale and thus the capability exists for providing realistic predictions of acoustic sensor performance as a function of the time of day.

C. COOLING CYCLE

An example of model response at OWS PAPA during a period of net cooling was also studied. Beginning at 03 GMT 23 November net upward heat flux over a 36-day period is illustrated by Figure 13. This figure shows fluctuations in SLB up to 40 gcal/cm^2/hour in 24 hours, and a decrease in magnitude of the daily insolation values from the August period. Net cooling occurs during the period as the upward heat flux is larger than downward heat flux. Maximum upward heat flux occurs on day 28. During the same period the surface wind stress shows large variations (Figure 14). Of particular note are the forecast winds at 06 GMT and 18 GMT, which are consistently smaller in magnitude than the 00 GMT and 12 GMT observations, thus giving a sawtooth appearance to the stress field. Small errors in wind velocity are amplified as the mechanical generation of turbulence is a function of the velocity to the third power.

The overall affect of this atmospheric forcing is to deepen the MLD (Figure 15) and decrease the temperature of the well-mixed layer (Figure 17). The model MLD is initialized at 84 meters and deepens at a nearly constant rate to 108 meters after 36 days. The observed MLD values are consistently 12 meters shallower than the model for the first 12 days. Observed MLD values are consistent as they reflect the sharp

negative thermal gradients below the well-mixed layer and a positive gradient associated with the seasonal halocline of the North Pacific. Figure 21 clearly shows that these gradients are persistent throughout the period. When the model is initialized six hours later at 09 GMT on 23 November 1974, the agreement between the data and model improves, as shown in Figure 16. As in the heating case, this emphasizes the sensitivity of the model to the initialization profiles. Also demonstrated again is the tendency for the model results to improve when wind induced turbulence (occurring at day 15 of Figures 15 and 16) mechanically mixes to the level of the observed data and decreases the temperature of the overlying water column.

During the 36-day period the model MLT showed a net decrease of $1.5^{\circ}C$. Figure 16 illustrates this decrease occurred at a nearly constant rate. The agreement between the data and model MLT is fairly good as the data shows the same $1.5^{\circ}C$ decrease in temperature. Of particular interest is the fluctuations in FNWC SST analysis values (Figure 17). Beginning at day 1 the FNWC SST values begin sinusoidal fluctuations which agree with observations when data is present (one exception occurs at day 9 when observations and FNWC SST disgree by $.8^{\circ}C$) but deviate from the model up to $\pm .8^{\circ}C$ at days 5 and 8 when observations are absent. In this case the model provides a more consistent SST evolution than the FNWC SST analysis when no observations are present. Figure 18 demonstrates the ability to simulate the response of the upper ocean thermal structure to a net change in heat content of the well-mixed layer. Below the permanent halocline the initialization procedure used has wiped out the lower thermal structure.

These results are similar to the findings at the five other OWS. During periods of net upward heat flux the MLD increases and the MLT decreases. Diurnal fluctuations do not appear due to the decrease in solar radiation, increase in SLB during the winter season and the larger input of mechanical mixing due to increased stress. During periods of light stress the slab depth decreases as expected. Again due to the sparcity of data for verification, evaluation of the model simulations at the other stations was inconclusive. Another point of encouragement is that similar model results were obtained by Camp and Elsberry (1977) from observed atmospheric forcing data. This further demonstrates that the synoptic-scale forcing functions used in this study contain sufficient resolution for driving this model.

V. SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the feasibility of using synoptic scale atmospheric data to produce ocean thermal structure responses. In the cases studied the atmospheric forcing functions derived from synoptic scale fields contained diurnal and synoptic scale fluctuations. The model demonstrated qualitatively the ability to determine the response of the ocean thermal structure to fluctuating atmospheric forcing on these time scales. Before any quantitative measure of the model performance is made, the Bathy profiles used to initialize the model and verify its results need to be of higher quality. One possibility is to use the original recording trace of each Bathy observation for digitization for model use. Another possibility is high resolution data collected on scientific cruises such as the Mixed-Layer Experiment (MILE) at OWS PAPA. The model was run for a maximum of 864 hours. This limit was determined solely by the length of continuous historical data available for study. When the model is driven by these forcing functions the ocean thermal structure response contains diurnal and synoptic time scales. This response matched the fluctuations in observed data. Thus in areas of low Bathy coverage a reasonable dynamic ocean thermal structure could be produced for long periods of time. One implication is that an ocean thermal structure forecast could be produced up to 72 hours from the time of a Bathy observation from 72-hr atmospheric forecasts.

TABLE I. OWS POSITIONS, P1 is number of Bathys in area from 8 August to 28 August 1974 and P2 is number of Bathys in the area from 21 November to 30 December 1974.

OWS	LAT.	LONG.	P1	P2
H	38°N	71°W	53	70
I	37°N	20°W	33	5
M	66°N	2°E	33	14
P	50°N	145°W	195	104
T	29°N	135°E	4	2
N	30°N	140°W	18	14

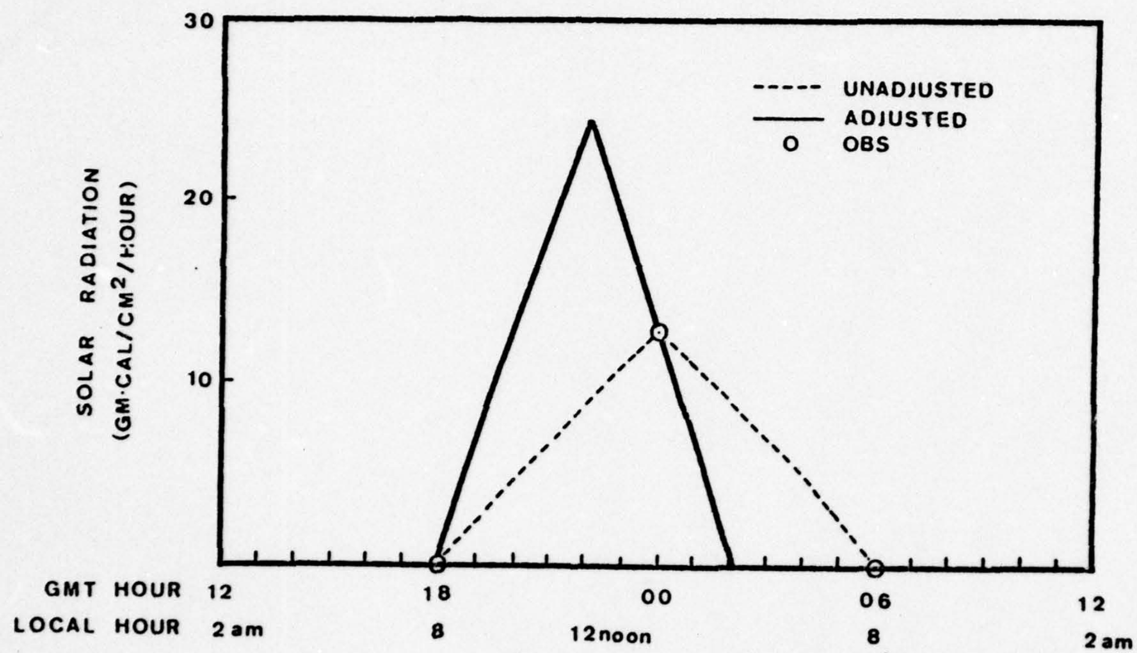

Figure 1. Solar Radiation adjusted and unadjusted for local noon and Sunrise/Sunset at OWS PAPA for 12 GMT 4 December to 12 GMT 5 December 1974.

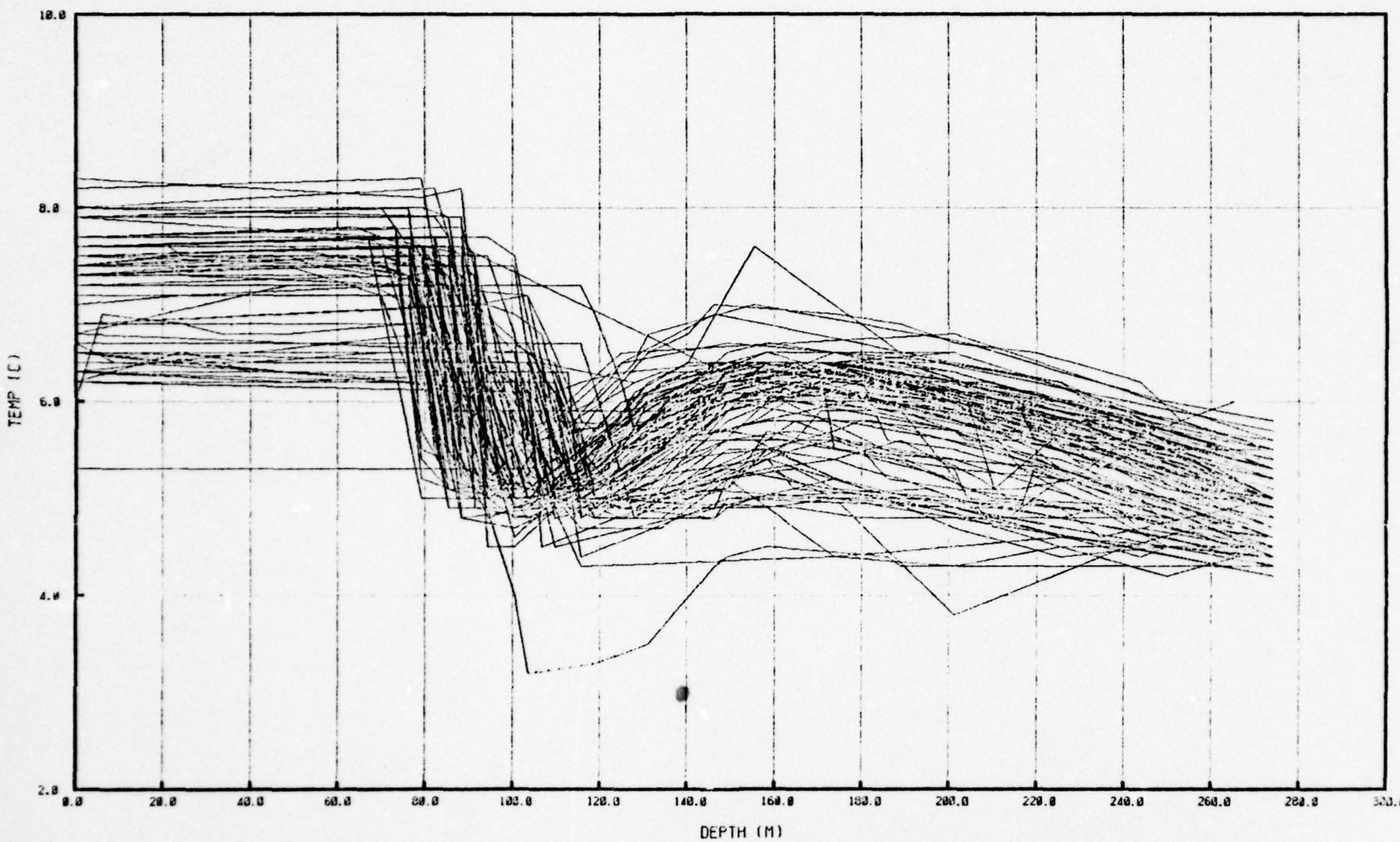

Figure 2. Bathythermograph overplot for OWS PAPA - 21 November to 31 December 1974.

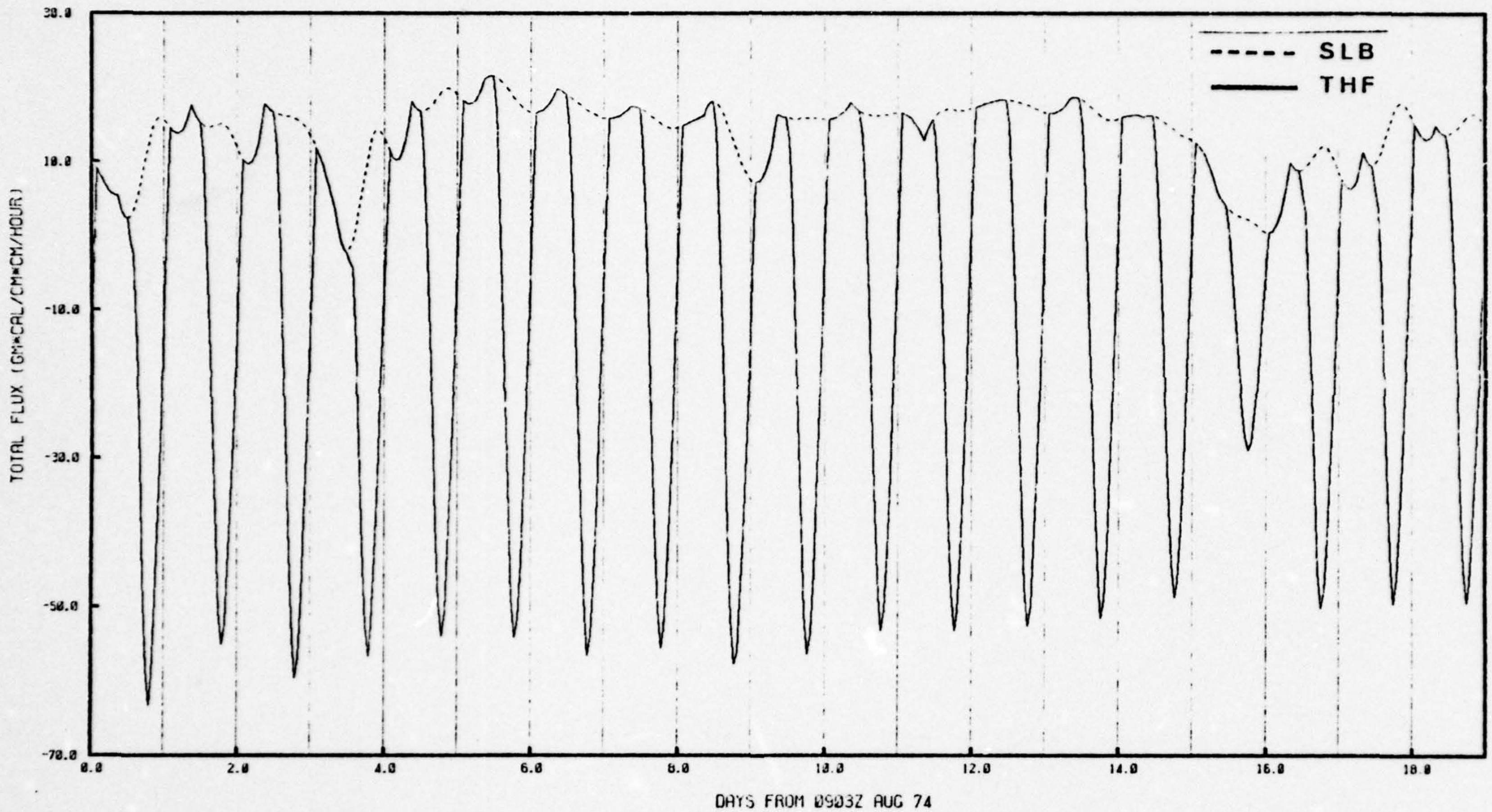

Figure 3. Total heat flux at OWS PAPA - 03 GMT 9 August to 03 GMT 28 August 1974. SLB is the sum of sensible, latent and backscattered radiation. THF is SLB plus Solar Radiation.

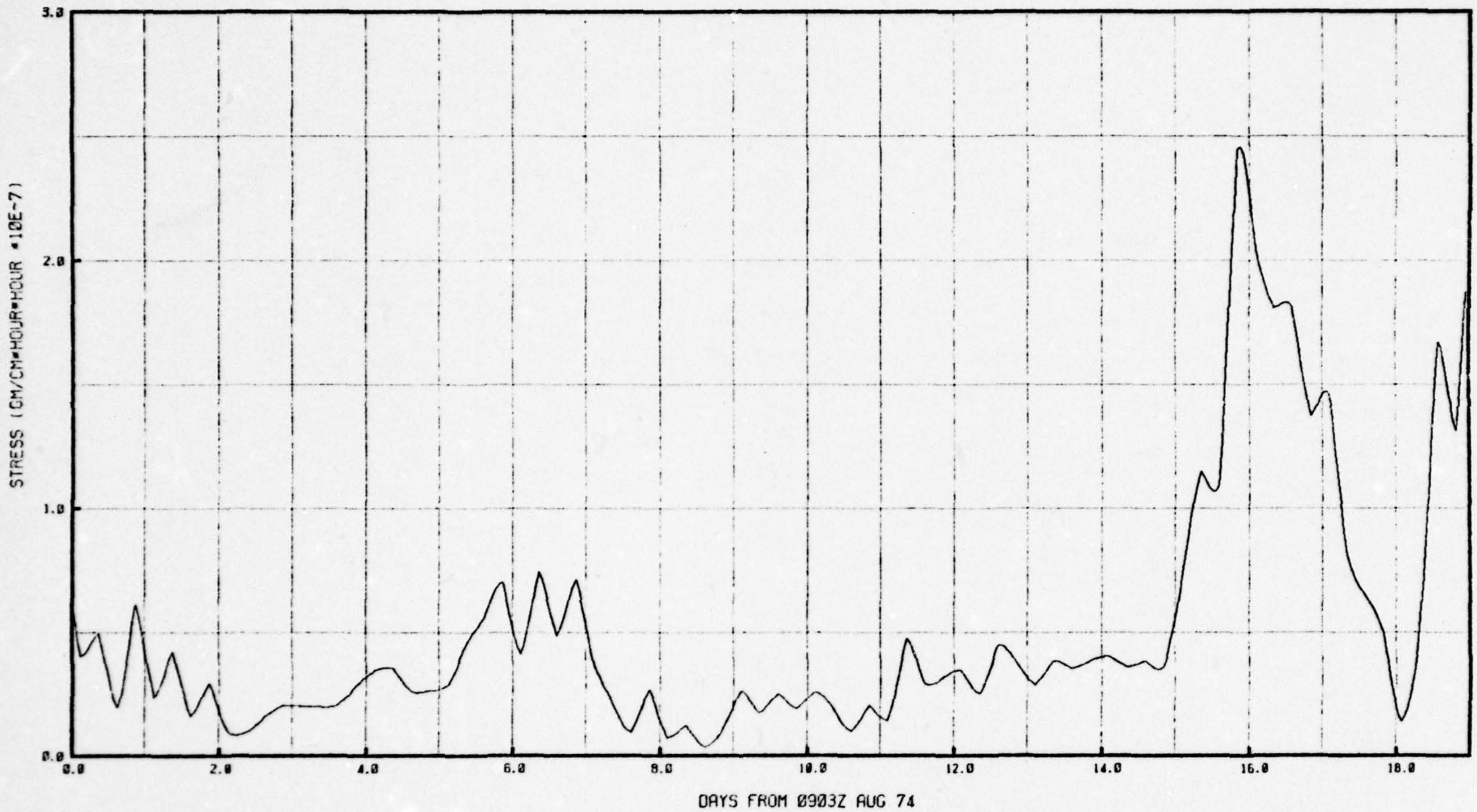

Figure 4. Wind stress at OWS PAPA - 03 GMT 9 August to 03 GMT 28 August 1974.

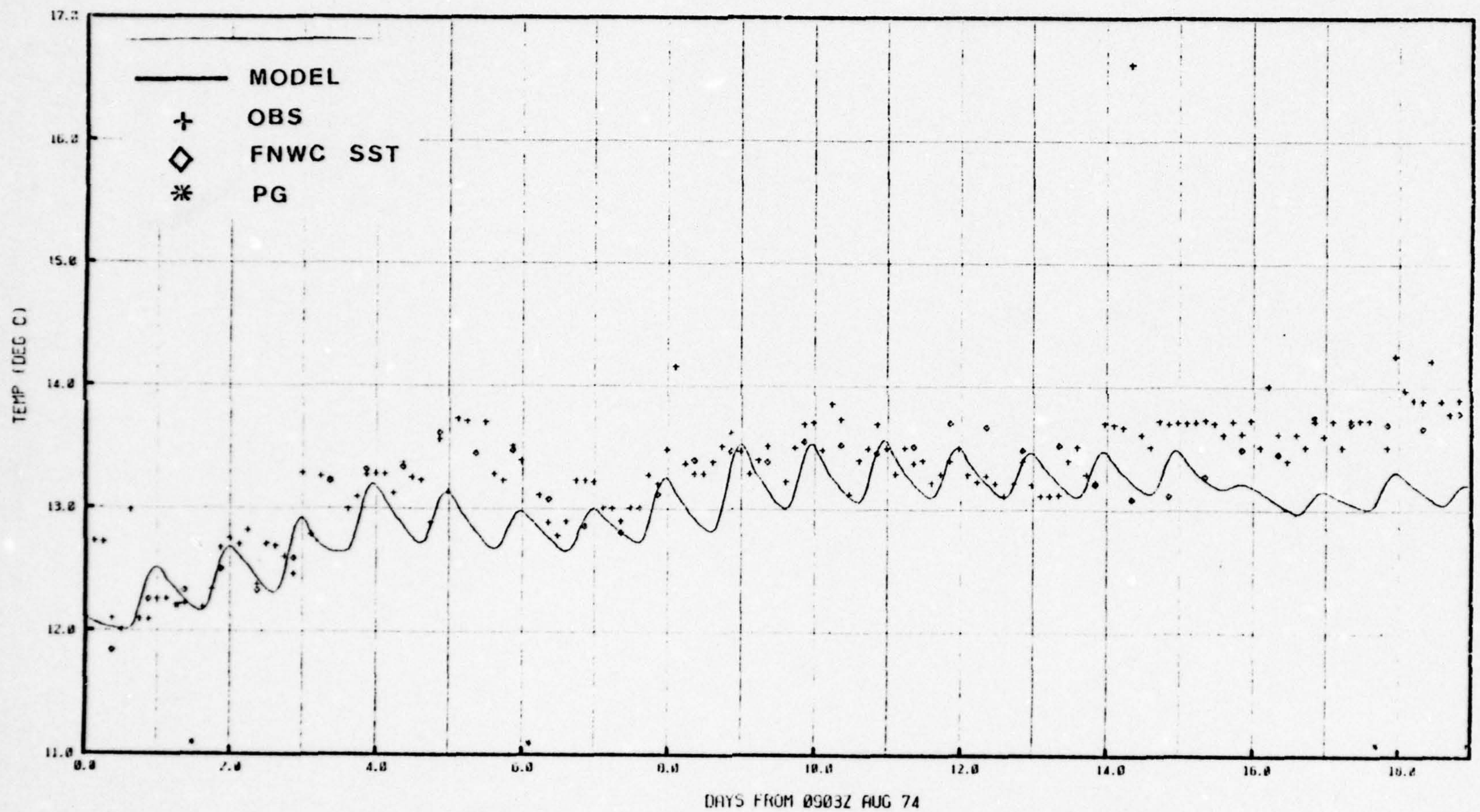

Figure 5. Mixed-layer temperature at OWS PAPA - 03 GMT 9 August to 28 August 1974. MODEL is model temperature of isothermal layer, OBS is the observed temperature of isothermal layer, FNWC SST is FNWC Sea Surface Temperature analysis and PG indicates a positive gradient was encountered above MLD.

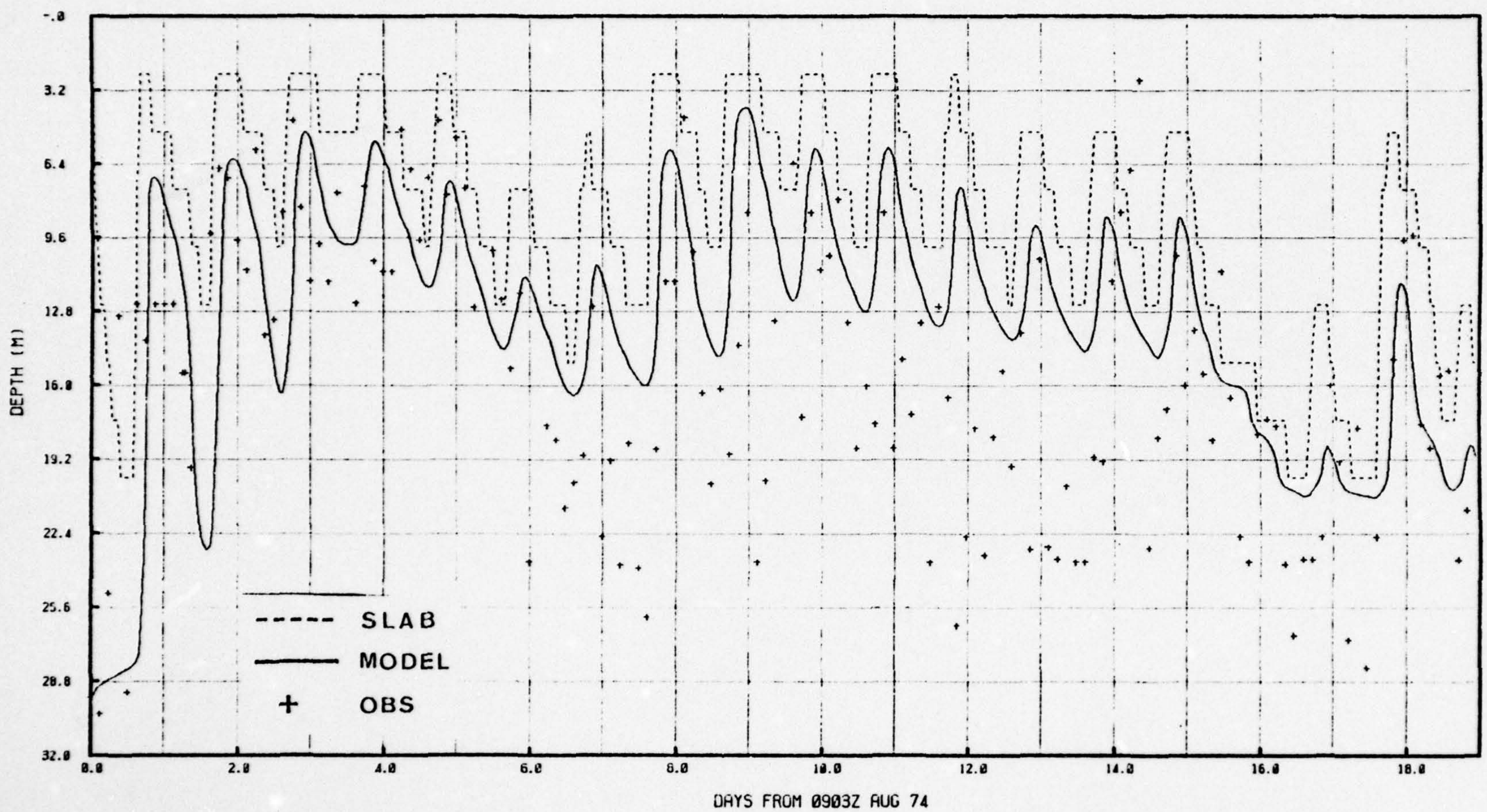

Figure 6. Mixed-layer depth at OWS PAPA - 03 GMT 9 August to 28 August 1974. MODEL is model MLD defined as depth .2°C cooler than isothermal temperature, SLAB is model depth of isothermal layer and OBS is observed MLD.

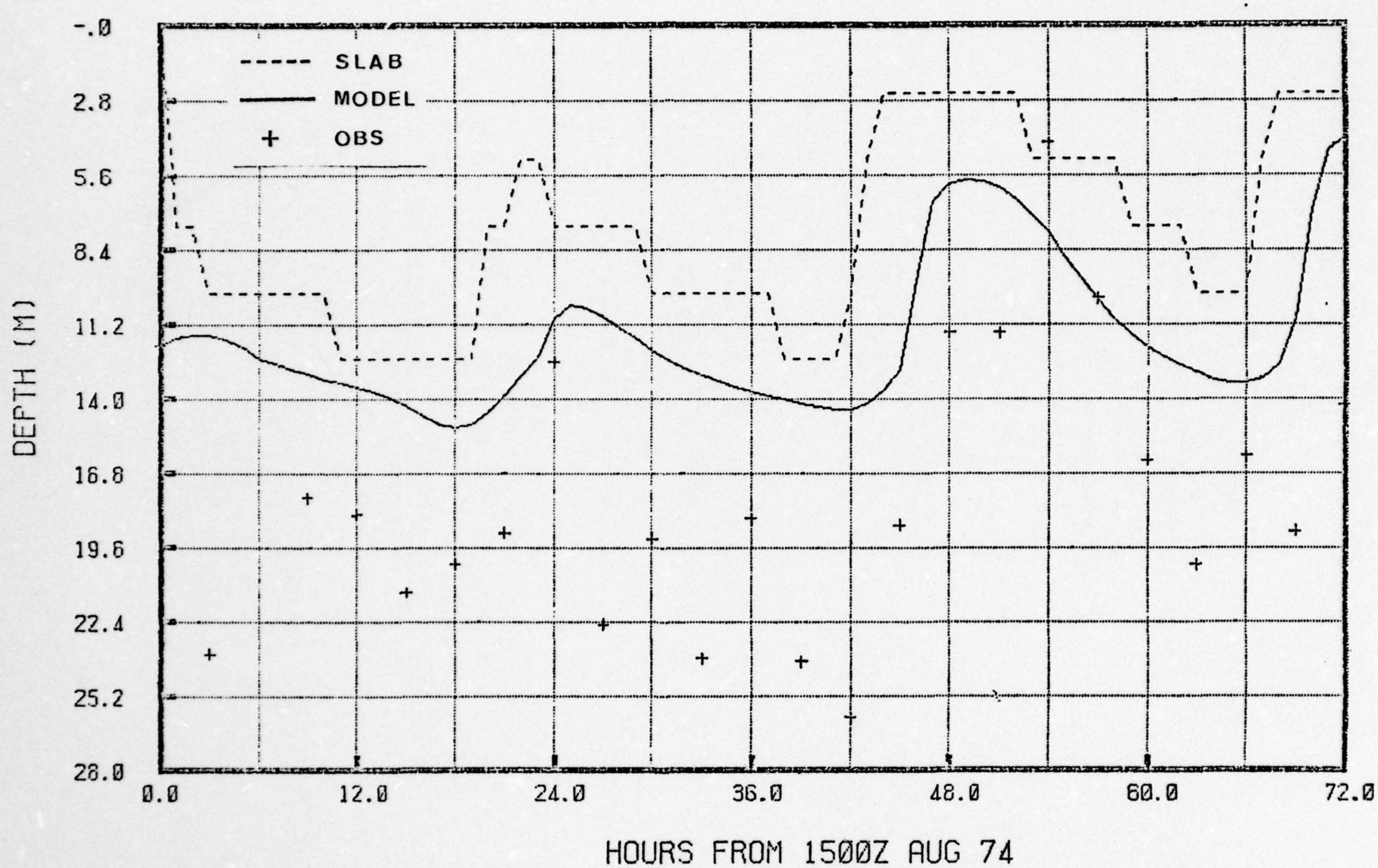

Figure 7. Similar to Figure 6 except for 00 GMT 15 August to 00 GMT 18 August 1974.

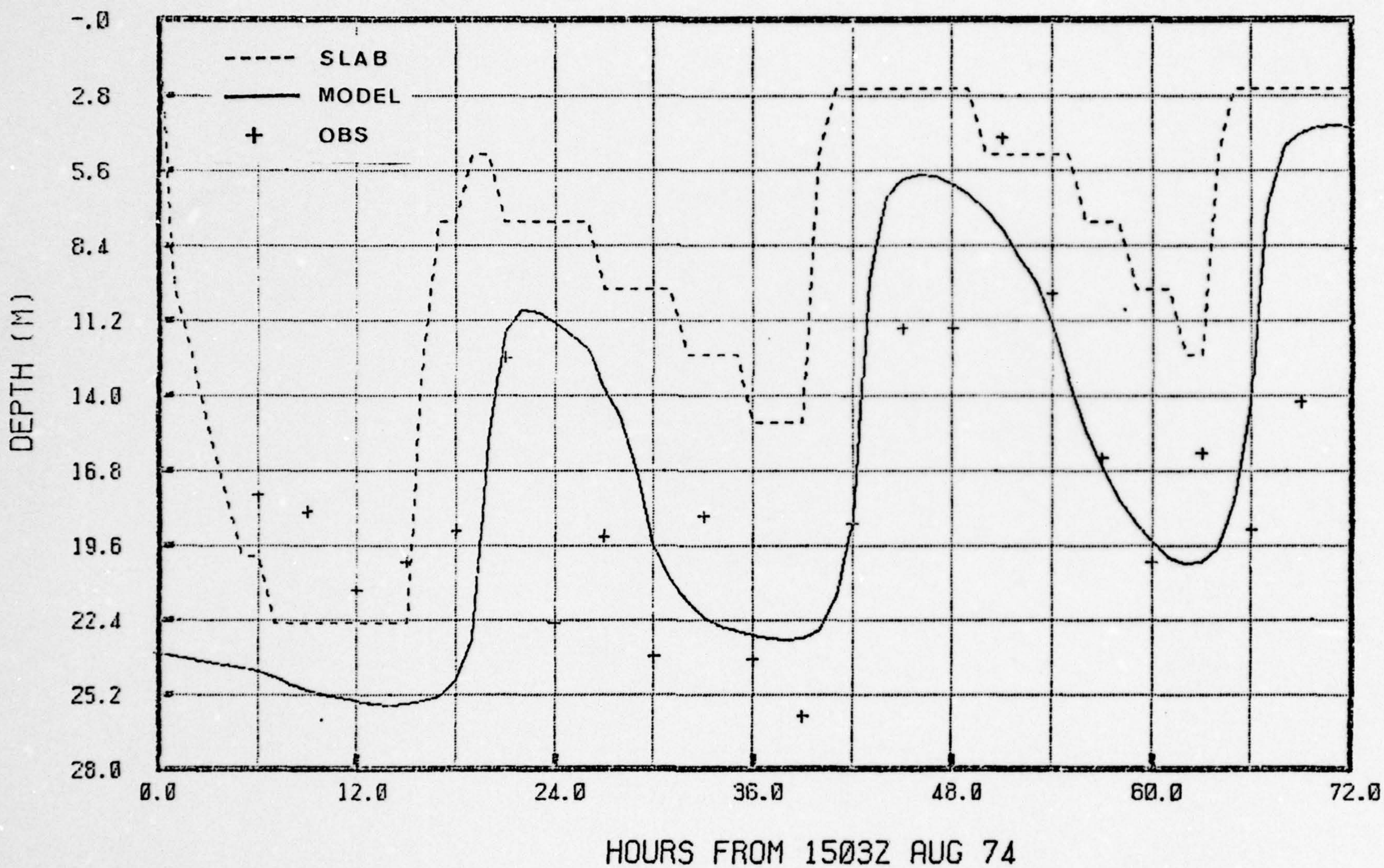

Figure 8. Similar to Figure 6 except for 03 GMT 15 August to 03 GMT 18 August 1974.

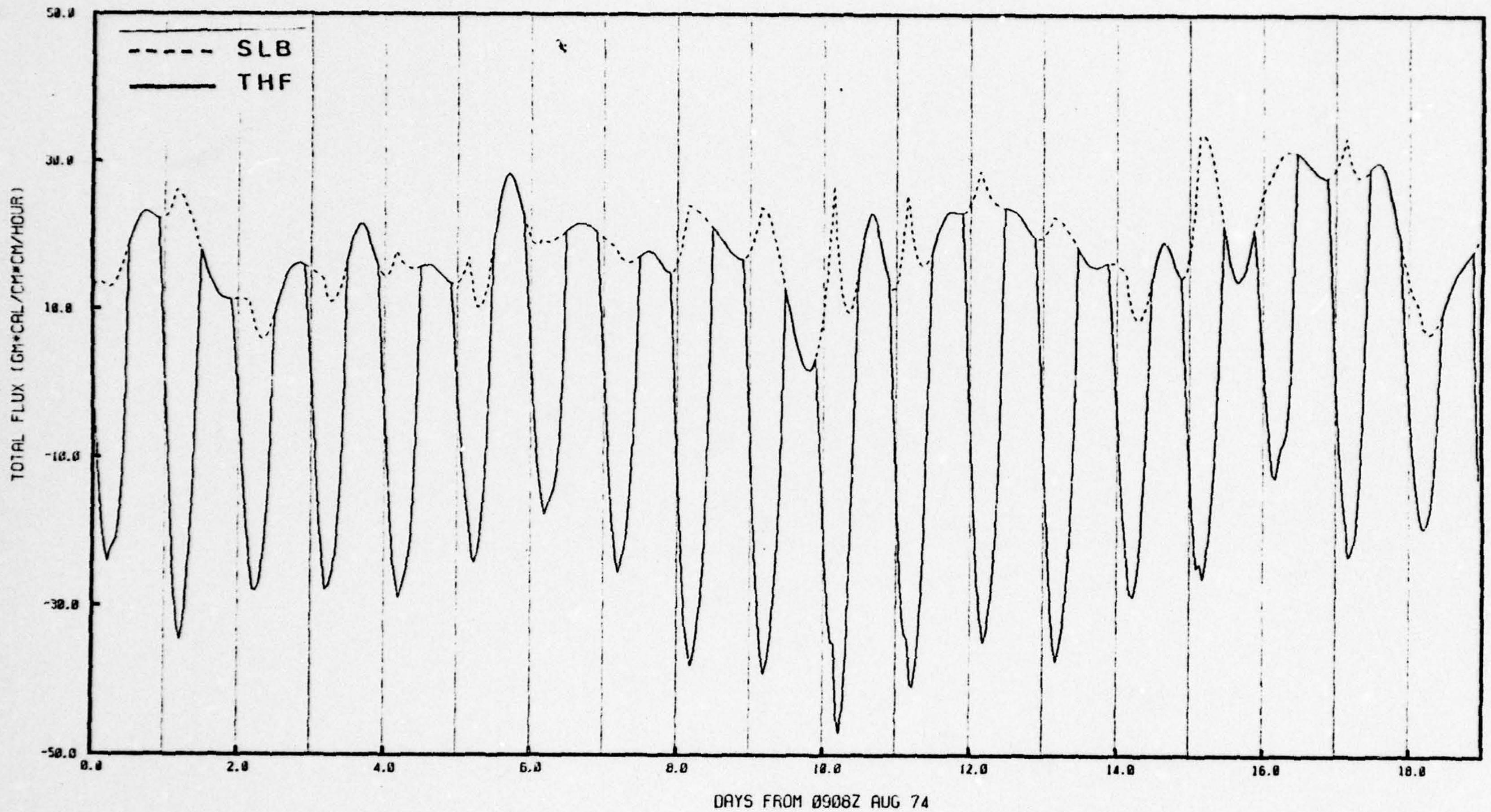

Figure 9. Similar to Figure 3 except for OWS INDIA - 08 GMT 9 August to 08 GMT 28 August 1974.

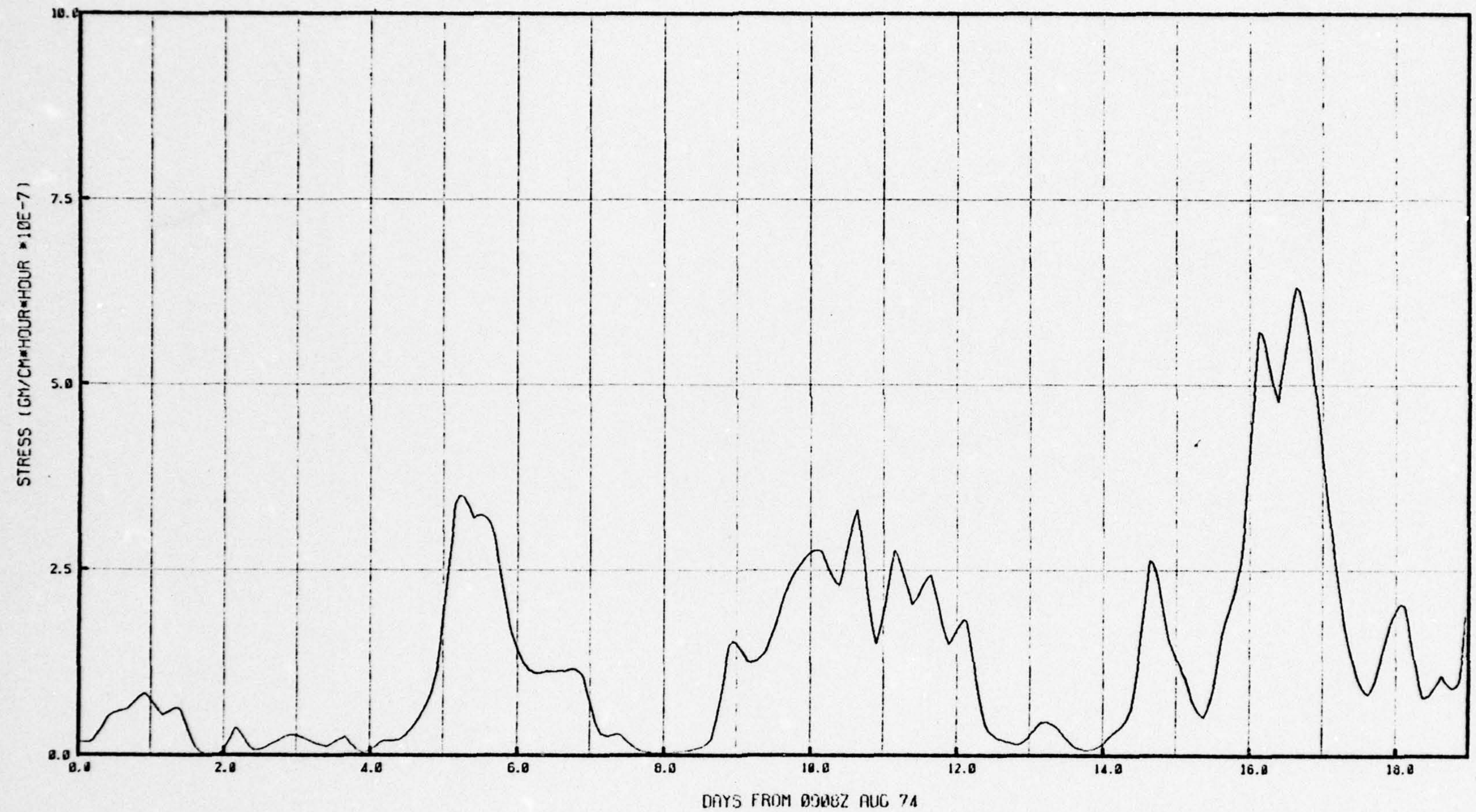

Figure 10. Wind stress at OWS INDIA - 08 GMT 9 August to 08 GMT 28 August 1974.

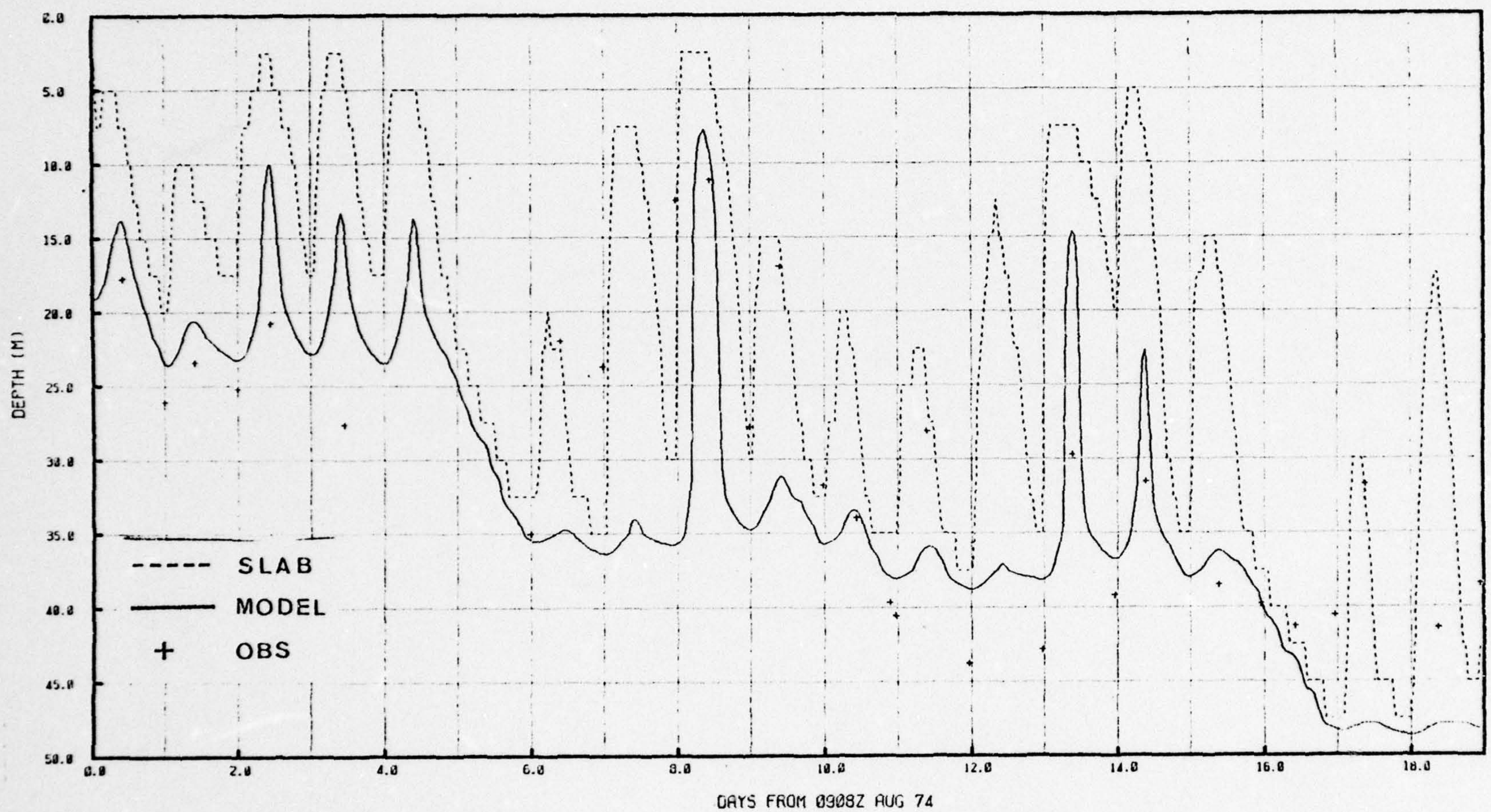

Figure 11. Similar to Figure 6 except for OWS INDIA - 08 GMT 9 August to 08 GMT 28 August 1974.

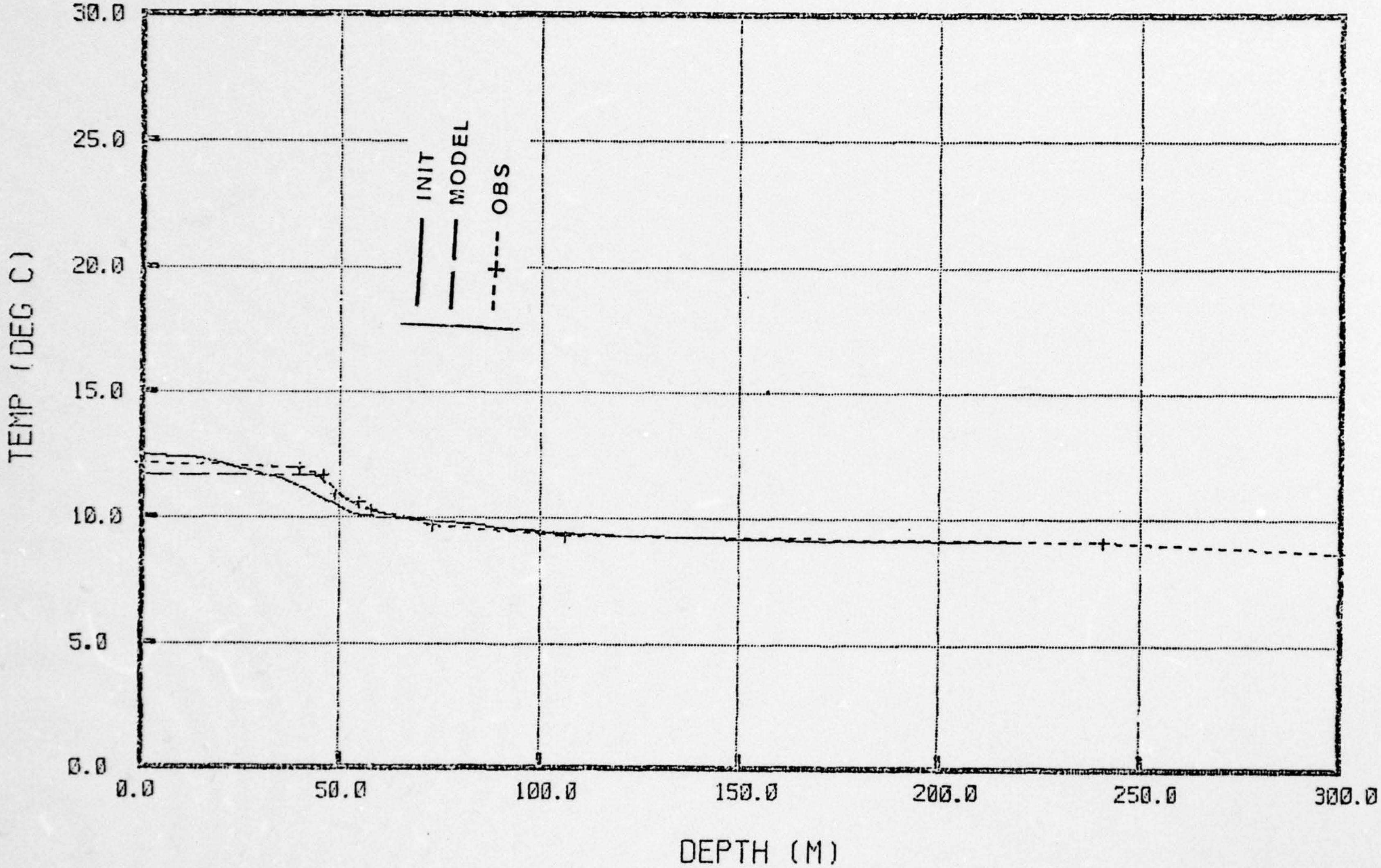

Figure 12. Depth versus temperature profile at OWS INDIA for 08 GMT 28 August 1974. INITIAL is profile used to initialize, MODEL is model profile and OBS is observed verifying profile.

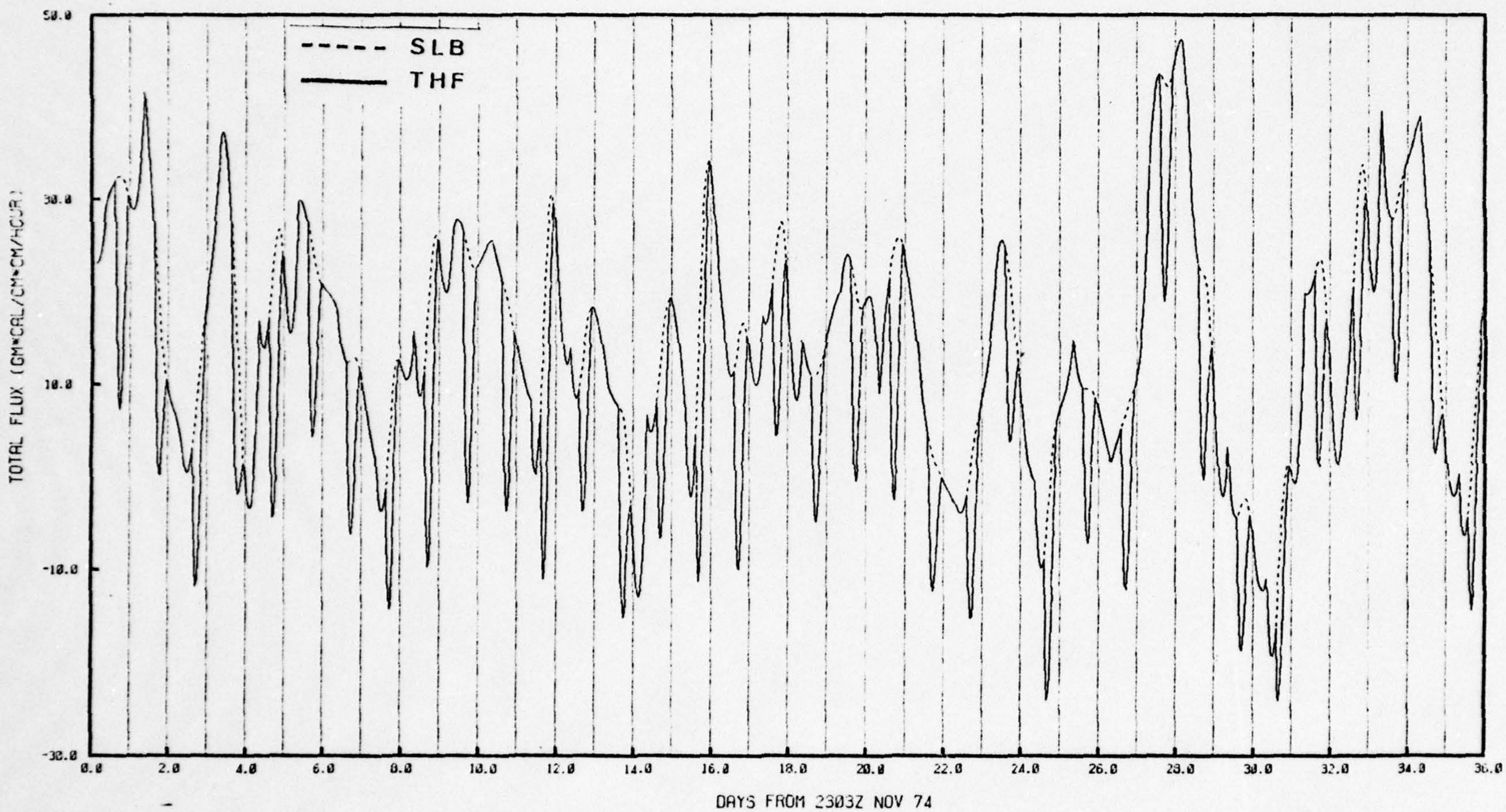

Figure 13. Similar to Figure 3 except at OWS PAPA 03 GMT 23 November to 03 GMT 29 December 1974.

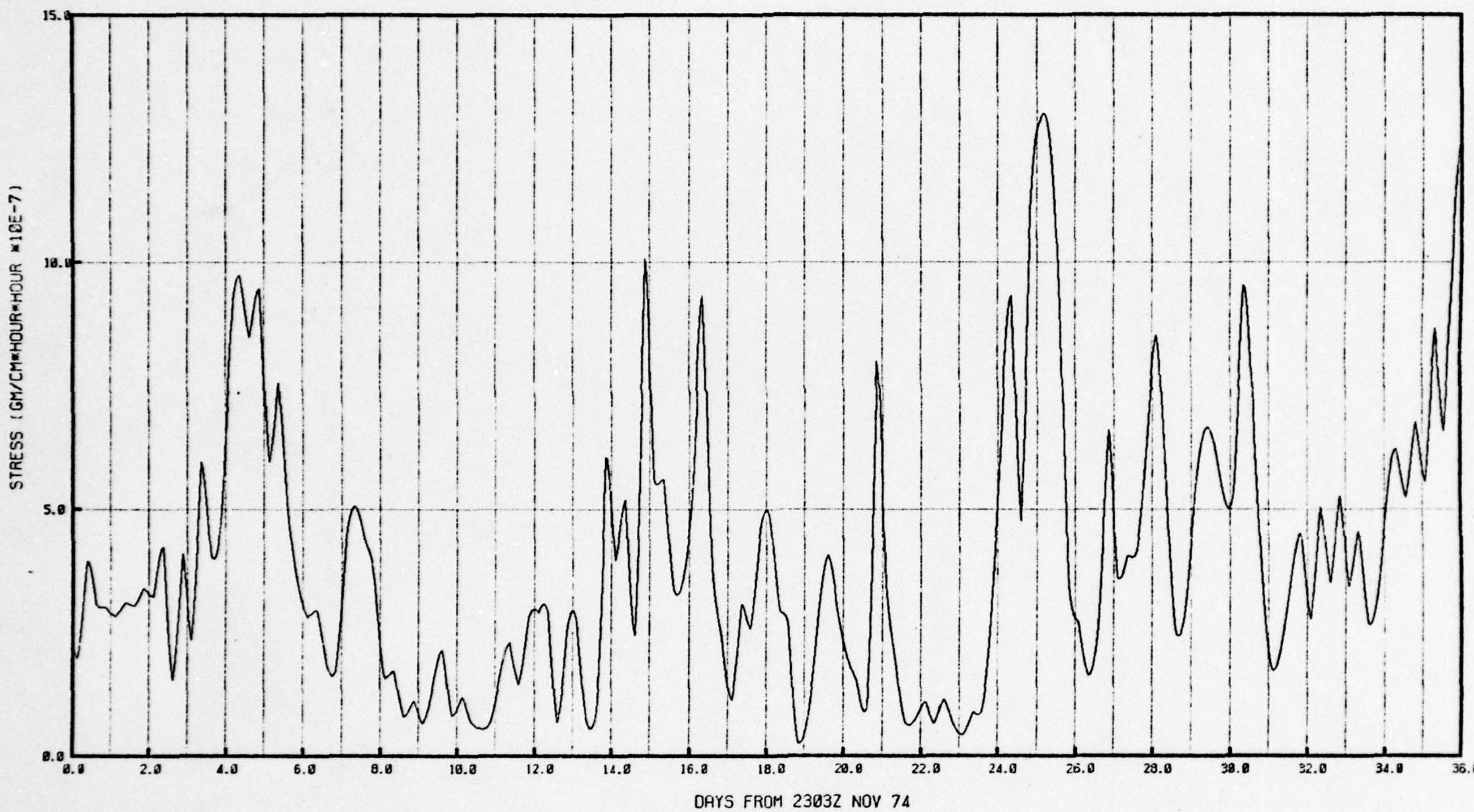

Figure 14. Wind stress at OWS PAPA - 03 GMT 23 November to 03 GMT 29 December 1974.

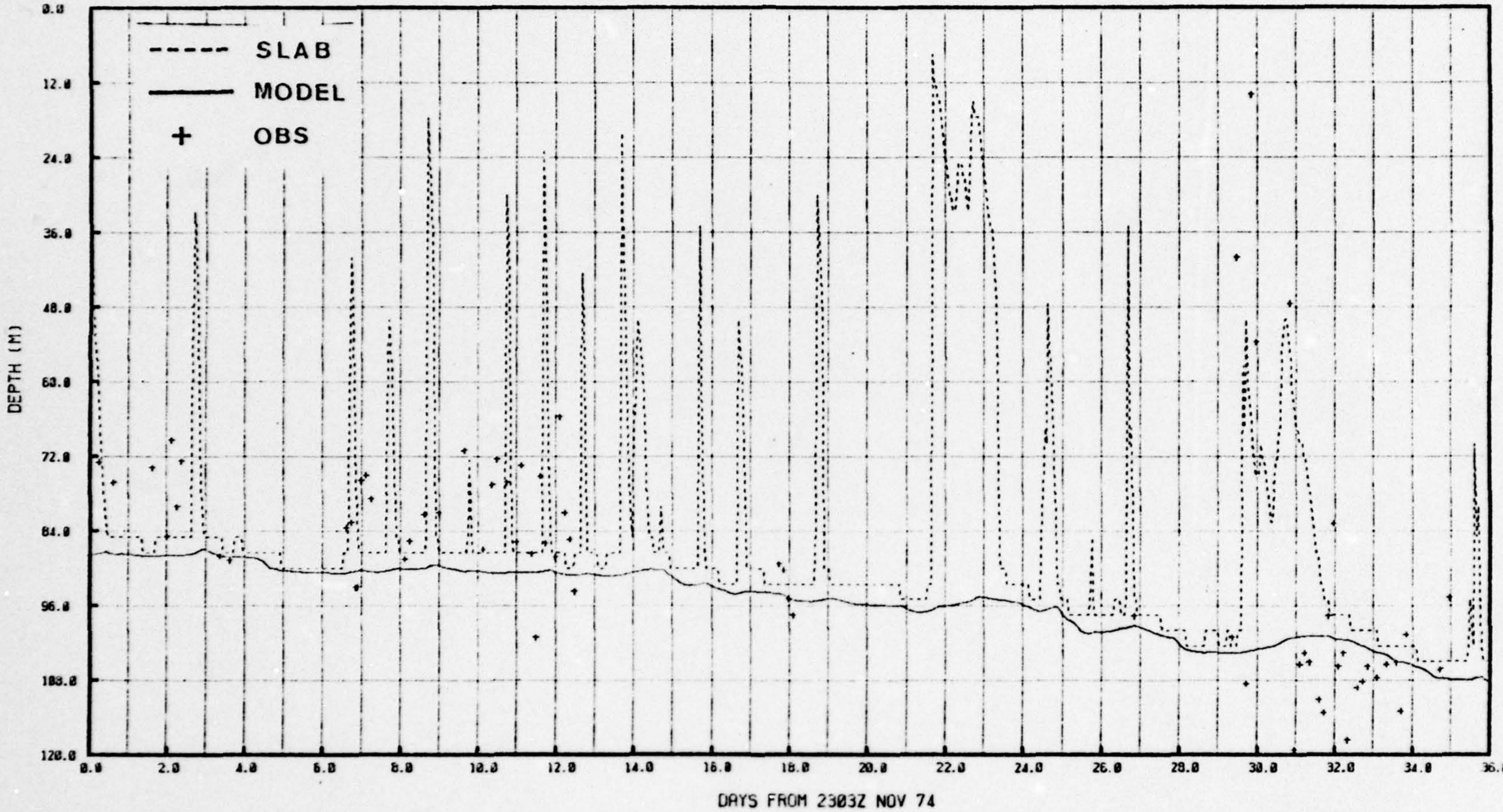

Figure 15. Similar to Figure 6 except for 03 GMT 23 November to 03 GMT 29 December 1974.

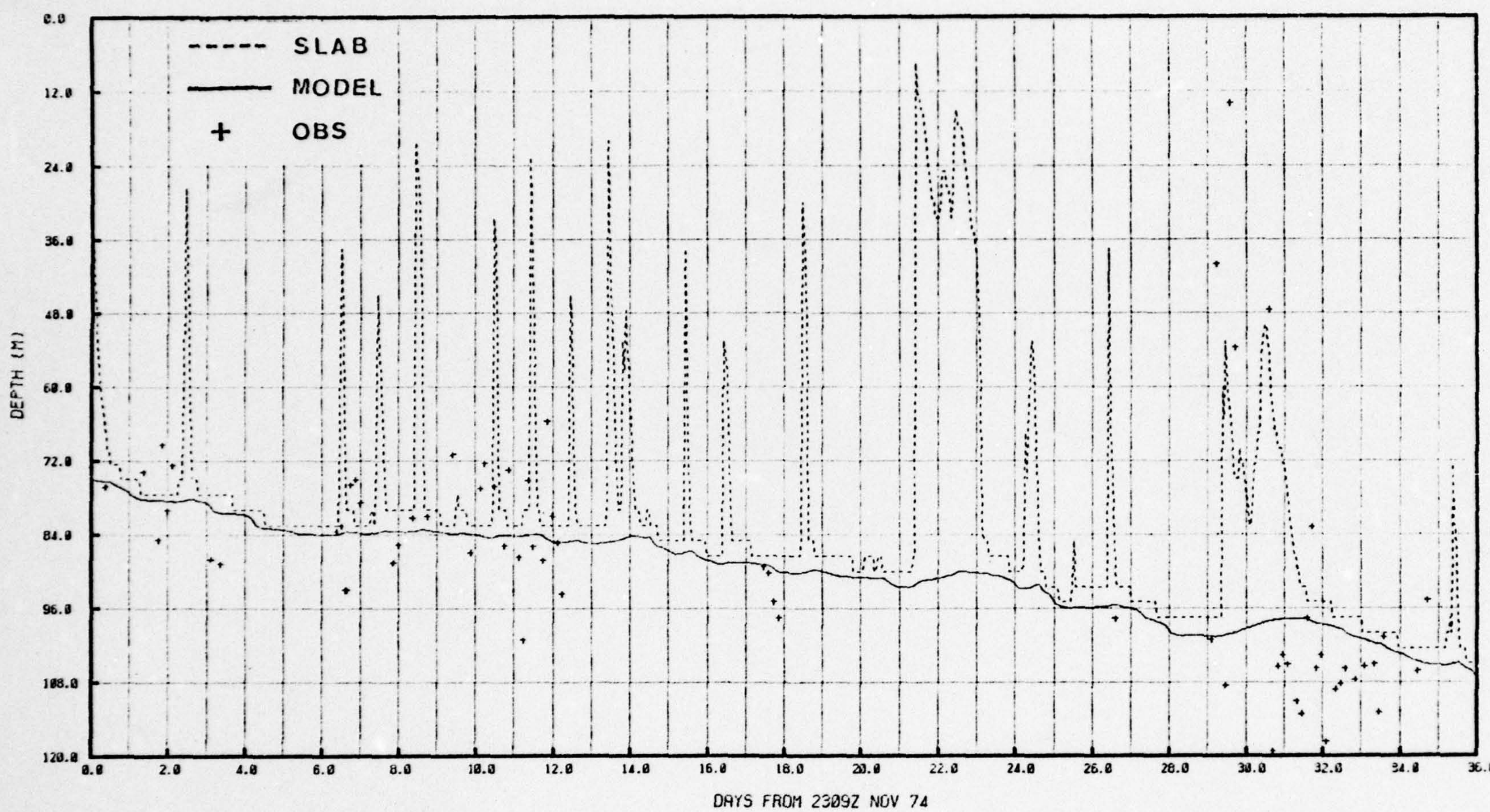

Figure 16. Similar to Figure 6 except for 09 GMT 23 November to 03 GMT 29 December 1974.

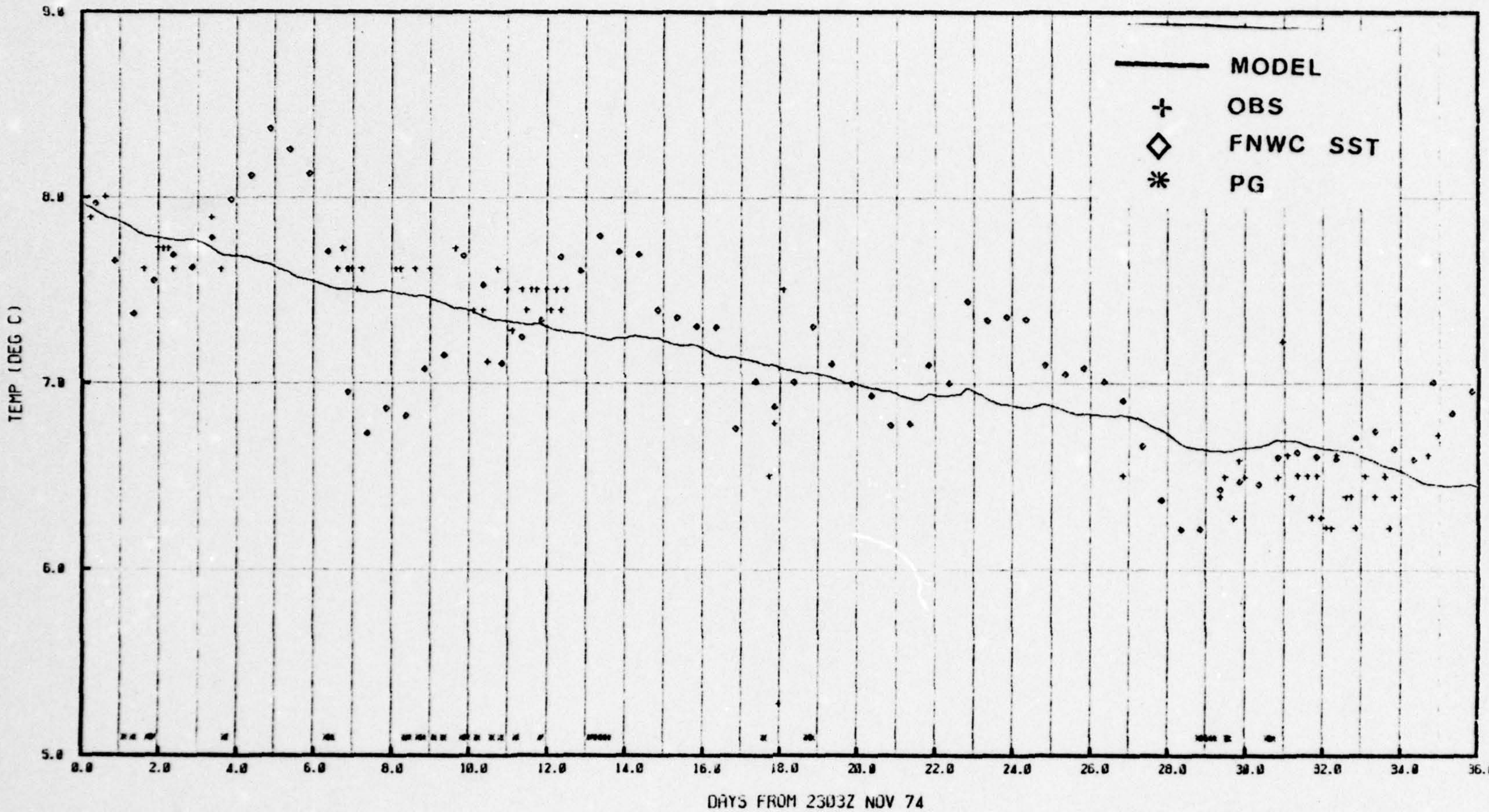

Figure 17. Similar to Figure 5 except for 03 GMT 23 November to 03 GMT 29 December 1974.

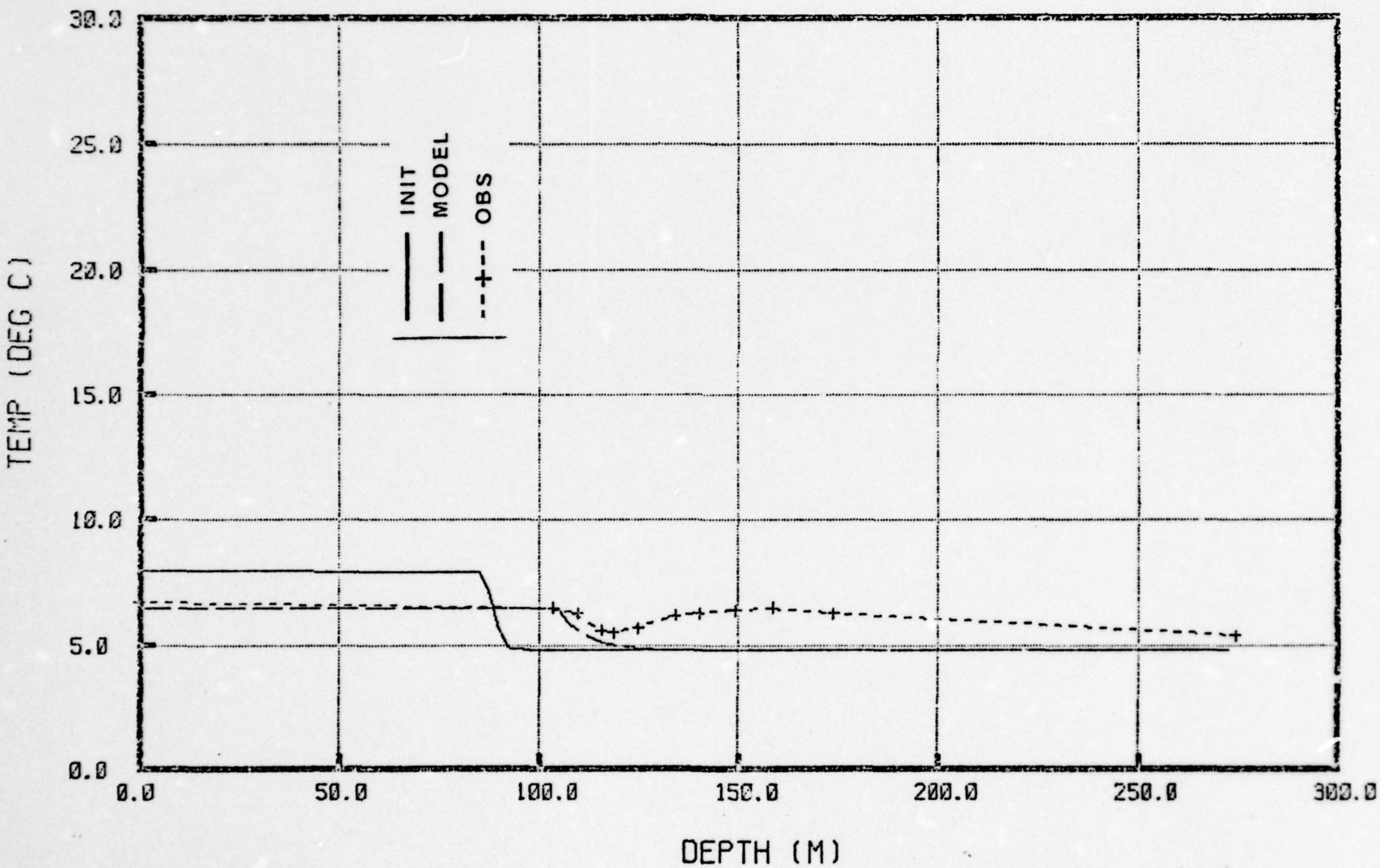

Figure 18. Similar to Figure 12 except at OWS PAPA for 03 GMT 29 December 1974.

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